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(71) Applicant (*for all designated States except US*): **ALCOA INC.** [US/US]; 201 Isabella Street, Pittsburgh, PA 15212-5858 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **RAY, Siba, P.** [US/US]; Alcoa Technical Center, 100 Technical Drive, Alcoa Center, PA 15069-0001 (US). **LIU, Xinghua** [CN/US]; Alcoa Technical Center, 100 Technical Drive, Alcoa Center, PA 15069-0001 (US). **WEIRAUCH, Douglas, A., Jr.** [US/US]; Alcoa Technical Center, 100 Technical Drive, Alcoa Center, PA 15069-0001 (US).

(74) Agents: **HANDELMAN, Joseph, H.**; Ladas & Parry, 26 West 61st Street, New York, NY 10023 et al. (US).

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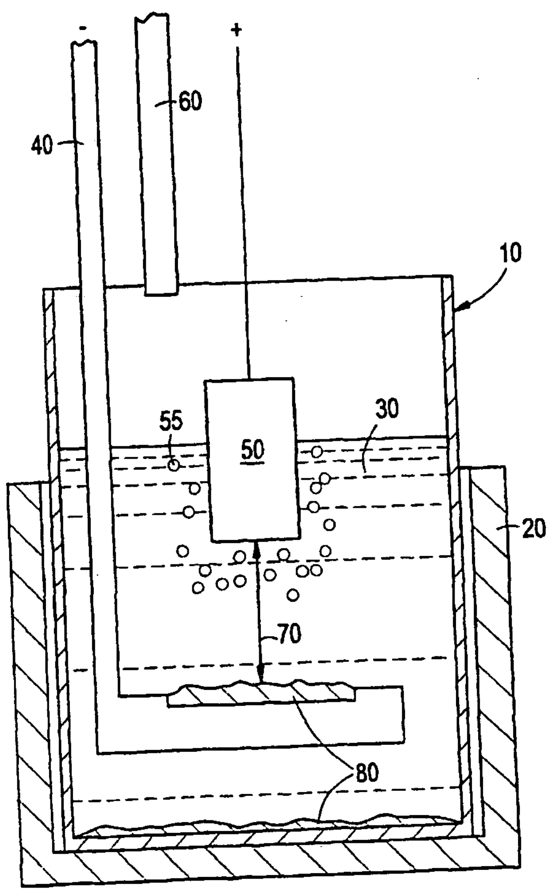
(54) Title: ELECTROLYTIC PRODUCTION OF HIGH PURITY ALUMINUM USING INERT ANODES



(57) Abstract: A method of producing commercial purity aluminum in an electrolytic reduction cell comprising inert anodes is disclosed. The method produces aluminum having acceptable levels of Fe, Cu and Ni impurities. The inert anodes used in the process preferably comprise a cermet material comprising ceramic oxide phase portions and metal phase portions.

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ELECTROLYTIC PRODUCTION OF HIGH PURITY ALUMINUM USING INERT ANODES

The present invention relates to the electrolytic production of aluminum. More particularly, the invention relates to the production of commercial purity aluminum with an electrolytic reduction cell including inert anodes.

The energy and cost efficiency of aluminum smelting can be significantly reduced with the use of inert, non-consumable and dimensionally stable anodes. Replacement of traditional carbon anodes with inert anodes should allow a highly productive cell design to be utilized, thereby reducing capital costs. Significant environmental benefits are also possible because inert anodes produce no CO_2 or CF_4 emissions. Some examples of inert anode compositions are provided in U.S. Patent Nos. 4,374,050; 4,374,761; 4,399,008; 4,455,211; 4,582,585; 4,584,172; 4,620,905; 5,794,112 and 5,865,980, assigned to the assignee of the present application. These patents are incorporated herein by reference.

A significant challenge to the commercialization of inert anode technology is the anode material. Researchers have been searching for suitable inert anode materials since the early years of the Hall-Heroult process. The anode material must satisfy a number of very difficult conditions. For example, the material must not react with or dissolve to any significant extent in the cryolite electrolyte. It must not react with oxygen or corrode in an oxygen-containing atmosphere. It should be thermally stable at temperatures of about 1,000°C. It must be relatively inexpensive and should have good mechanical strength. It must have high electrical conductivity at the smelting cell operating temperatures, e.g., about 900-1,000°C, so that the voltage drop at the anode is low.

In addition to the above-noted criteria, aluminum produced with the inert anodes should not be contaminated with constituents of the anode material to any appreciable extent. Although the use of inert anodes in aluminum electrolytic reduction cells has been proposed in the past, the use of such inert anodes has not been put into commercial practice. One reason for this lack of implementation has been the long-standing inability to produce aluminum of commercial grade purity with inert anodes. For example, impurity levels of Fe, Cu and/or Ni have been found to be unacceptably high in aluminum produced with known inert anode

materials.

The present invention has been developed in view of the foregoing, and to address other deficiencies of the prior art.

An aspect of the present invention is to provide a process for producing high purity aluminum using inert anodes. The method includes the steps of passing current between an inert anode and a cathode through a bath comprising an electrolyte and aluminum oxide, and recovering aluminum comprising a maximum of 0.15 weight percent Fe, 0.1 weight percent Cu, and 0.03 weight percent Ni.

Additional aspects and advantages of the invention will occur to persons skilled in the art from the following detailed description thereof.

Fig. 1 is a partially schematic sectional view of an electrolytic cell with an inert anode that is used to produce commercial purity aluminum in accordance with the present invention.

Fig. 2 is a ternary phase diagram illustrating amounts of iron, nickel and zinc oxides present in an inert anode that may be used to make commercial purity aluminum in accordance with an embodiment of the present invention.

Fig. 3 is a ternary phase diagram illustrating amounts of iron, nickel and cobalt oxides present in an inert anode that may be used to make commercial purity aluminum in accordance with another embodiment of the present invention.

Fig. 1 schematically illustrates an electrolytic cell for the production of commercial purity aluminum which includes an inert anode in accordance with an embodiment of the present invention. The cell includes an inner crucible 10 inside a protection crucible 20. A cryolite bath 30 is contained in the inner crucible 10, and a cathode 40 is provided in the bath 30. An inert anode 50 is positioned in the bath 30. An alumina feed tube 60 extends partially into the inner crucible 10 above the bath 30. The cathode 40 and inert anode 50 are separated by a distance 70 known as the anode-cathode distance (ACD). Commercial purity aluminum 80 produced during a run is deposited on the cathode 40 and on the bottom of the crucible 10.

As used herein, the term "inert anode" means a substantially non-consumable anode which possesses satisfactory corrosion resistance and stability

during the aluminum production process. In a preferred embodiment, the inert anode comprises a cermet material.

As used herein, the term "commercial purity aluminum" means aluminum which meets commercial purity standards upon production by an electrolytic reduction process. The commercial purity aluminum comprises a maximum of 0.2 weight percent Fe, 0.1 weight percent Cu, and 0.034 weight percent Ni. In a preferred embodiment, the commercial purity aluminum comprises a maximum of 0.15 weight percent Fe, 0.034 weight percent Cu, and 0.03 weight percent Ni. More preferably, the commercial purity aluminum comprises a maximum of 0.13 weight percent Fe, 0.03 weight percent Cu, and 0.03 weight percent Ni. Preferably, the commercial purity aluminum also meets the following weight percentage standards for other types of impurities: 0.2 maximum Si, 0.03 Zn and 0.03 Co. The Si impurity level is more preferably kept below 0.15 or 0.10 weight percent.

Inert anodes of the present invention preferably have ceramic phase portions and metal phase portions. The ceramic phase typically comprises at least 50 weight percent of the anode, preferably from about 70 to about 90 weight percent. It is noted that for every numerical range or limit set forth herein, all numbers with the range or limit including every fraction or decimal between its stated minimum and maximum, are considered to be designated and disclosed by this description.

The ceramic phase portions preferably comprise iron and nickel oxides, and at least one additional oxide such as zinc oxide and/or cobalt oxide. For example, the ceramic phase may be of the formula; $Ni_{1-x-y} Fe_{2-x} M_y O$; where M is preferably Zn and/or Co; x is from 0 to 0.5; and y is from 0 to 0.6. More preferably X is from 0.05 to 0.2, and y is from 0.01 to 0.5. Table 1 lists some ternary Fe-Ni-Zn-O materials that may be suitable for use as the ceramic phase of a cermet inert anode.

TABLE 1

Sample I.D.	Nominal Composition	Elemental Weight Percent Fe, Ni, Zn	Structural Types
5412	$NiFe_2O_4$	48, 23.0, 0.15	$NiFe_2O_4$
5324	$NiFe_2O_4$ + NiO	34, 36, 0.06	$NiFe_2O_4$, NiO
E4	$Zn_{0.05}Ni_{0.95}Fe_2O_4$	43, 22, 1.4	$NiFe_2O_4$ TU^*
E3	$Zn_{0.1}Ni_{0.9}Fe_2O_4$	43, 20, 2.7	$NiFe_2O_4$ TU^*
E2	$Zn_{0.25}Ni_{0.75}Fe_2O_4$	40, 15, 5.9	$NiFe_2O_4$ TU^*
E1	$ZZn_{0.25}Ni_{0.75}Fe_{1.90}O_4$	45, 18, 7.8	$NiFe_2O_4$ TU^*
E	$Zn_{0.5}Ni_{0.5}Fe_2O_4$	45, 12, 13	$(ZnNi)Fe_2O_4$, TP^+ ZnO^S
F	$ZnFe_2O_4$	43, 0.03, 24	$ZnFe_2O_4$, TP^+ ZnO
H	$Zn_{0.5}NiFe_{1.5}O_4$	33, 23, 13	$(ZnNi)Fe_2O_4$, NiO^S
J	$Zn_{0.5}Ni_{1.5}FeO_4$	26, 39, 10	$NiFe_2O_4$, MP $^+$NiO
L	$ZnNiFeO_4$	22, 23, 27	$(ZnNi)Fe_2O_4$, NiO^S, ZnO
ZD6	$Zn_{0.05}Ni_{1.05}Fe_{1.9}O_4$	40, 24, 1.3	$NiFe_2O_4$ TU^*
ZD5	$Zn_{0.1}Ni_{1.1}Fe_{1.8}O_4$	29, 18, 2.3	$NiFe_2O_4$ TU^*
ZD3	$Zn_{0.12}Ni_{0.94}Fe_{1.88}O_4$	43, 23, 3.2	$NiFe_2O_4$ TU^*
ZD1	$Zn_{0.12}Ni_{0.94}Fe_{1.88}O_4$	40, 20, 11	$(ZnNi)Fe_2O_4$ TU^*
DH	$Zn_{0.18}Ni_{0.96}Fe_{1.8}O_4$	42, 23, 4.9	$NiFe_2O_4$, TP $^+$NiO
DI	$Zn_{0.08}Ni_{1.17}Fe_{1.5}O_4$	38, 30, 2.4	$NiFe_2O_4$, MP $^+$NiO, TU^*
DJ	$Zn_{0.17}Ni_{1.1}Fe_{1.5}O_4$	36, 29, 4.8	$NiFe_2O_4$, MP $^+$NiO
BC2	$Zn_{0.33}Ni_{0.67}O$	0.11, 52, 25	NiO^S, TU^*

* TU means trace unidentified; +TP means trace possible; +MP means minor possible; S means shifted peak.

Fig. 2 is a ternary phase diagram illustrating the amounts of Fe_2O_3, NiO and ZnO starting materials used to make the compositions listed in Table 1, which may be used as the ceramic phase(s) of cermet inert anodes. Such inert anodes may in turn be used to produce commercial purity aluminum in accordance with the present invention.

In one embodiment, when Fe_2O_3, NiO and ZnO are used as starting materials for making an inert anode, they are typically mixed together in ratios of

20 to 99.09 mole percent NiO, 0.01 to 51 mole percent Fe_2O_3, and zero to 30 mole percent ZnO. Preferably, such starting materials are mixed together in ratios of 45 to 65 mole percent NiO, 20 to 45 mole percent Fe_2O_3, and 0.01 to 22 mole percent ZnO.

Table 2 lists some ternary Fe_2O_3/NiO/CoO materials that may be suitable as the ceramic phase.

TABLE 2

Sample I.D.	Nominal Composition	Analyzed Elemental Wgt. % Fe, Ni, Co	Structural Types
CF	$CoFe_2O_4$	44, 0.17, 24	$CoFe_2O_4$
NCF1	$Ni_{0.5}Co_{0.5}Fe_2O_4$	44, 12, 11	$NiFe_2O_4$
NCF2	$Ni_{0.7}Co_{0.3}Fe_2O_4$	45, 16, 7.6	$NiFe_2O_4$
NCF3	$Ni_{0.7}Co_{0.3}Fe_{1.95}O_4$	42, 18, 6.9	$NiFe_2O_4$, TU*
NCF4	$Ni_{0.85}Co_{0.15}Fe_{1.95}O_4$	44, 20, 3.4	$NiFe_2O_4$
NCF5	$Ni_{0.85}Co_{0.5}Fe_{1.9}O_4$	45, 20, 7.0	$NiFe_2O_4$, NiO, TU*
NF	$NiFe_2O_4$	48, 23, 0	N/A

* TU means trace unidentified

Fig. 3 is a ternary phase diagram illustrating the amounts of Fe_2O_3, NiO and CoO starting materials used to make the compositions listed in Table 2, which may be used as the ceramic phase(s) of cermet inert anodes. Such inert anodes may in turn be used to produce commercial purity aluminum in accordance with the present invention.

The cermet inert anodes used in accordance with a preferred aluminum production method of the present invention include at least one metal phase, for example, a base metal and at least one noble metal. Copper and silver are preferred base metals. However, other electrically conductive metals may optionally be used to replace all or part of the copper or silver. Furthermore, additional metals such as Co, Ni, Fe, Al, Sn, Nb, Ta, Cr, Mo, W and the like may be alloyed with the base metal. Such base metals may be provided from individual or alloyed powders of the metals, or as oxides of such metals.

The noble metal preferably comprises at least one metal selected from

Ag, Pd, Pt, Au, Rh, Ru, Ir and Os. More preferably, the noble metal comprises Ag, Pd, Pt, Ag and/or Rh. Most preferably, the noble metal comprises Ag, Pd or a combination thereof. The noble metal may be provided from individual or alloyed powders of the metals, or as oxides of such metals, e.g., silver oxide, palladium oxide, etc.

Preferably, metal phase(s) of the inert electrode comprises at least about 60 weight percent of the combined base metal and noble metal, more preferably at least about 80 weight percent. The presence of base metal/noble metal provides high levels of electrical conductivity through the inert electrodes. The base metal/noble metal phase may form either a continuous phase(s) within the inert electrode or a discontinuous phase(s) separated by the oxide phase(s).

The metal phase of the inert electrode typically comprises from about 50 to about 99.99 weight percent of the base metal, and from about 0.01 to about 50 weight percent of the noble metal(s). Preferably, the metal phase comprises from about 70 to about 99.95 weight percent of the base metal, and from about 0.05 to about 30 weight percent of the noble metal(s). More preferably, the metal phrase comprises from about 90 to about 99.9 weight percent of the base metal, and from about 0.1 to about 10 weight percent of the noble metal(s).

The types and amounts of base and noble metals contained in the metal phase of the inert anode are selected in order to substantially prevent unwanted corrosion, dissolution or reaction of the inert electrodes, and to withstand the high temperatures which the inert electrodes are subjected to during the electrolytic metal reduction process. For example, in the electrolytic production of aluminum, the production cell typically operates at sustained smelting temperatures above 800°C, usually at temperatures of 900-980°C. Accordingly, inert anodes used in such cells should preferably have melting points above 800°C, more preferably above 900°C, and optimally above about 1,000°C.

In one embodiment of the invention, the metal phase comprises copper as the base metal and a relatively small amount of silver as the noble metal. In this embodiment, the silver content is preferably less than about 10 weight percent, more preferably from about 0.2 to about 9 weight percent, and optimally from about 0.5 to about 8 weight percent, remainder copper. By combining such

relatively small amounts of Ag with such relatively large amounts of Cu, the melting point of the Cu-Ag alloy phase is significantly increased. For example, an alloy comprising 95 weight percent Cu and 5 weight percent Ag has a melting point of approximately 1,000°C, while an alloy comprising 90 weight percent Cu and 10 weight percent Ag forms a eutectic having a melting, point of approximately 780°C. This difference in melting points is particularly significant where the alloys are to be used as part of inert anodes in electrolytic aluminum reduction cells, which typically operate at smelting temperatures of greater than 800°C.

In another embodiment of the invention, the metal phase comprises copper as the base metal and a relatively small amount of palladium as the noble metal. In this embodiment, the Pd content is preferably less than about 20 weight percent, more preferably from about 0.1 to about 10 weight percent.

In a further embodiment of the invention, the metal phase comprises silver as the base metal and a relatively small amount of palladium as the noble metal. In this embodiment, the Pd content is preferably less than about 50 weight percent, more preferably from about 0.05 to about 30 weight percent, and optimally from about 0.1 to about 20 weight percent. Alternatively, silver may be used alone as the metal phase of the anode.

In another embodiment of the invention, the metal phase comprises Cu, Ag and Pd. In this embodiment, the amounts of Cu, Ag and Pd are preferably selected in order to provide an alloy having a melting point above 800°C, more preferably above 900°C, and optimally above about 1,000°C. The silver content is preferably from about 0.5 to about 30 weight percent of the metal phase, while the Pd content is preferably from about 0.01 to about 10 weight percent. More preferably, the Ag content is from about 1 to about 20 weight percent of the metal phase, and the Pd content is from about 0.1 to about 10 weight percent. The weight ratio of Ag to Pd is preferably from about 2:1 to about 100:1, more preferably from about 5:1 to about 20:1.

In accordance with a preferred embodiment of the present invention, the types and amounts of base and noble metals contained in the metal phase are selected such that the resultant material forms at least one alloy phase having an increased melting point above the eutectic melting point of the particular alloy

system. For example, as discussed above in connection with the binary Cu-Ag alloy system, the amount of the Ag addition may be controlled in order to substantially increase the melting point above the eutectic melting point of the Cu-Ag alloy. Other noble metals, such as Pd and the like, may be added to the binary Cu-Ag alloy system in controlled amounts in order to produce alloys having melting points above the eutectic melting points of the alloy systems. Thus, binary, ternary, quaternary, etc. alloys may be produced in accordance with the present invention having sufficiently high melting points for use as part of inert electrodes in electrolytic metal production cells.

The inert anodes may be formed by techniques such as powder sintering, sol-gel processes, slip casting and spray forming. Preferably, the inert electrodes are formed by powder techniques in which powders comprising the oxides and metals are pressed and sintered. The inert anode may comprise a monolithic component of such materials, or may comprise a substrate having at least one coating or layer of such material.

Prior to combining the ceramic and metal powders, the ceramic powders, such as NiO, Fe_2O_3 and ZnO or CoO, may be blended in a mixer. Optionally, the blended ceramic powders may be ground to a smaller size before being transferred to a furnace where they are calcined, e.g., for 12 hours at 1,250°C. The calcination produces a mixture made from oxide phases, for example, as illustrated in Figs. 2 and 3. If desired, the mixture may include other oxide powders such as Cr_2O_3.

The oxide mixture may be sent to a ball mill where it is ground to an average particle size of approximately 10 microns. The fine oxide particles are blended with a polymeric binder and water to make a slurry in a spray dryer. The slurry contains, e.g., about 60 wt.% solids and about 40 wt.% water. Spray drying the slurry produces dry agglomerates of the oxides that may be transferred to a V-blender and mixed with metal powders. The metal powders may comprise substantially pure metals and alloys thereof, or may comprise oxides of the base metal and/or noble metal.

In a preferred embodiment, about 1-10 parts by weight of an organic polymeric binder are added to 100 parts by weight of the metal oxide and metal

particles. Some suitable binders include polyvinyl alcohol, acrylic polymers, polyglycols, polyvinyl acetate, polyisobutylene, polycarbonates, polystyrene, polyacrylates, and mixtures and copolymers thereof. Preferably, about 3-6 parts by weight of the binder are added to 100 parts by weight of the metal oxides, copper and silver.

The V-blended mixture of oxide and metal powders may be sent to a press where it is isostatically pressed, for example at 10,000 to 40,000 psi, into anode shapes. A pressure of about 20,000 psi is particularly suitable for many applications. The pressed shapes may be sintered in a controlled atmosphere furnace supplied with an argon-oxygen gas mixture. Sintering temperatures of 1,000-1,400°C may be suitable. The furnace is typically operated at 1,350-1,385°C for 2-4 hours. The sintering process burns out any polymeric binder from the anode shapes.

The sintered anode may be connected to a suitable electrically conductive support member within an electrolytic metal production cell by means such as welding, brazing, mechanically fastening, cementing and the like.

The gas supplied during sintering preferably contains about 5-3,000 ppm oxygen, more preferably about 5-700 ppm and most preferably about 10-350 ppm. Lesser concentrations of oxygen result in a product having a larger metal phase than desired, and excessive oxygen results in a product having too much of the phase containing metal oxides (ceramic phase). The remainder of the gaseous atmosphere preferably comprises a gas such as argon that is inert to the metal at the reaction temperature.

Sintering anode compositions in an atmosphere of controlled oxygen content typically lowers the porosity to acceptable levels and avoids bleed out of the metal phase. The atmosphere may be predominantly argon, with controlled oxygen contents in the range of 17 to 350 ppm. The anodes may be sintered in a tube furnace at 1,30°C for 2 hours. Anode compositions sintered under these conditions typically have less than 0.5% porosity when the compositions are sintered in argon containing 70-150 ppm oxygen. In contrast, when the same anode compositions are sintered for the same time and at the same temperature in an argon atmosphere, porosities are substantially higher and the anodes may show various amounts of

bleed out of the metal phase.

The inert anode may include a cermet as described above successively connected in series to a transition region and a nickel end. A nickel or nickel-chromium alloy rod may be welded to the nickel end. The transition region, for example, may include four layers of graded composition, ranging from 25 wt.% Ni adjacent the cermet end and then 50, 75 and 100 wt.% Ni, balance the mixture of oxide and metal powders described above.

We prepared several inert anode compositions in accordance with the procedures described above having diameters of about 5/8 inch and length of about 5 inches. These compositions were evaluated in a Hall-Heroult test cell similar to that schematically illustrated in Fig. 1. The cell was operated for 100 hours at 960°C, with an aluminum fluoride to sodium fluoride bath ratio of 1.1 and alumina concentration maintained at about 7-7.5 wt.%. The anode compositions and impurity concentrations in aluminum produced by the cell are shown in Table 3. The impurity values shown in Table 3 represent the average of four test samples of the produced metal taken at four different locations after the 100 hour test period. Interim samples of the produced aluminum were consistently below the final impurity levels listed.

TABLE 3

Sample No.	Composition	Porosity	Fe	Cu	Ni
1	$3Ag-14Cu-42.9NiO-40.1Fe_2O_3$		0.191	0.024	0.044
2	$3Ag-14Cu-42.9NiO-40.1Fe_2O_3$		0.26	0.012	0.022
3	$3Ag-14Cu-26.45NiO-56.55Fe_2O_3$		0.375	0.13	0.1
4	$3Ag-14Cu-42.9NiO-40.1Fe_2O_3$		0.49	0.05	0.085
5	$3Ag-14Cu-42.9NiO-40.1Fe_2O_3$		0.36	0.034	0.027
6	$5Ag-10Cu-43.95NiO-41.05Fe_2O_3$		0.4	0.06	0.19
7	$3Ag-14Cu-42.9NiO-40.1Fe_2O_3$		0.38	0.095	0.12
8	$2Ag-15Cu-42.9NiO-40.1Fe_2O_3$		0.5	0.13	0.33
9	$2Ag-15Cu-42.9NiO-40.1Fe_2O_3$		0.1	0.16	0.26
10	$3Ag-11Cu-44.46NiO-41.54Fe_2O_3$		0.14	0.017	0.13
11	$1Ag-14Cu-27.75NiO-57.25Fe_2O_3$		0.24	0.1	0.143
12	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.127	0.07	0.011	0.0212
13	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.168	0.22	0.04	0.09
14	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.180	0.1	0.03	0.05
15	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.175	0.12	0.04	0.06
16	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.203	0.08	0.02	0.1
17	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.230	0.12	0.01	0.04
18	$1Ag-14Cu-27.96NiO-57.04Fe_2O_3$	0.184	0.17	0.18	0.47

Sample No.	Composition	Porosity	Fe	Cu	Ni
19	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.193	0.29	0.044	0.44
20	1Ag-14Cu-5ZnO-28.08NiO-56.92Fe_2O_3	0.201	0.16	0.02	0.02
21	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.144	0.44	0.092	0.15
22	1Ag-14Cu-5ZnO-28.08NiO-56.92Fe_2O_3	0.191	0.48	0.046	0.17
23	1Ag-14Cu-5ZnO-28.08NiO-56.92Fe_2O_3	0.214	0.185	0.04	0.047
24	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.201	0.15	0.06	0.123
25	1Ag-14Cu-5ZnO-28.08NiO-56.92Fe_2O_3	0.208	0.22	0.05	0.08
26	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.201	0.18	0.03	0.08
27	1Ag-14Cu-5ZnO-28.08NiO-56.92Fe_2O_3	0.252	0.21	0.05	0.08
28	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.203	0.21	0.057	0.123
29	1Ag-14Cu-27.35NiO-55.95Fe_2O_3-1.7ZnO	0.251	0.12	0.03	0.043
30	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.238	0.12	0.05	0.184
31	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.221	0.185	0.048	0.157
32	1Ag-14Cu-27.35NiO-55.95Fe_2O_3-1.7ZnO	0.256	0.16	0.019	0.028
33	1Pd-15Cu-40.48Fe_2O_3-43.32NiO-0.2ZnO	0.149	0.11	0.01	0.024
34	1Ag-14Cu-27.96NiO-57.04Fe_2O_3	0.241	0.186	0.05	0.22
35	3Pd-14Cu-42.91NiO-40.09Fe_2O_3	0.107	0.2	0.02	0.11
36	1Pt-15Cu-57.12Fe_2O_3-26.88NiO	0.105	0.14	0.024	0.041
37	1Pd-15Cu-57Fe_2O_3-27.8NiO-0.2ZnO	0.279	0.115	0.014	0.023

Sample No.	Composition	Porosity	Fe	Cu	Ni
38	1Pd-15Cu-40.48Fe_2O_3-43.32NiO-0.2ZnO	0.191	0.116	0.031	0.038
39	1Pd-15Cu-40.48Fe_2O_3-43.32NiO-0.2ZnO	0.253	0.115	0.07	0.085
40	0.5Pd-16Cu-43.27NiO-40.43Fe_2O_3-0.2ZnO	0.129	0.096	0.042	0.06
41	0.5Pd-16Cu-43.27NiO-40.43Fe_2O_3-0.2ZnO	0.137	0.113	0.033	0.084
42	0.1Pd-0.9Ag-15Cu-43.32NiO-40.48Fe_2O_3-0.2ZnO		0.18	0.04	0.066
43	0.05Pd-0.95Ag-14Cu-27.9NiO-56.9Fe_2O_3-0.2ZnO	0.184	0.038	0.013	0.025
44	0.1Pd-0.9Ag-14Cu-27.9NiO-56.9Fe_2O_3-0.2ZnO	0.148	0.18	0.025	0.05
45	0.1Pd-0.9Ag-14Cu-27.35NiO-55.95Fe_2O_3-1.7ZnO	0.142	0.09	0.02	0.03
46	0.05Pd-0.95Ag-14Cu-27.35NiO-55.95Fe_2O_3-1.7ZnO	0.160	0.35	0.052	0.084
47	1Ru-14Cu-27.35NiO-55.95Fe_2O_3-1.7ZnO	0.215	0.27	0.047	0.081
48	0.1Pd-0.9Ag-14Cu-55.81Fe_2O_3-27.49NiO-1.7ZnO	0.222	0.31	0.096	0.18
49	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.147	0.15	0.008	0.027
50	0.1Pd-2.7Ag(asAg_2O)-14.02Cu-26.9NiO-54.6Fe_2O_3-1.66ZnO	0.180	0.17	0.03	0.049
51	0.1Pd-0.9Ag(asAg_2O)-14Cu-25.49NiO-55.81Fe_2O_3-1.7ZnO	0.203	0.2	0.05	0.03
52	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.279	0.27	0.06	0.36
53	0.1Pd-0.9Ag(asAg_2O)-14Cu-25.49NiO-55.81Fe_2O_3-1.7ZnO	0.179	0.07	0.023	0.02
54	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.321	0.15	0.05	0.028
55	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.212	0.19	0.02	0.075
56	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.194	0.13	0.01	0.02

Sample No.	Composition	Porosity	Fe	Cu	Ni
57	1.0Ag(asAg_2O)-14Cu(as CuO)-27.5NiO-55.8Fe_2O_3-1.7ZnO	0.202	0.12	0.023	0.03
58	1.86Ag(asAg_2O)-14.02Cu-27.21NiO-55.23Fe_2O_3-1.68ZnO	0.241	0.10	0.01	0.02

The results in Table 3 show low levels of aluminum contamination by the inert anodes. In addition, the inert anode wear rate was extremely low in each sample tested. Optimization of processing parameters and cell operation may further improve the purity of aluminum produced in accordance with the invention.

Inert anodes are particularly useful in electrolytic cells for aluminum production operated at temperatures in the range of about 800-1,000°C. A particularly preferred cell operates at a temperature of about 900-980°C, preferably about 930-970°C. An electric current is passed between the inert anode and a cathode through a molten salt bath comprising an electrolyte and an oxide of the metal to be collected. In a preferred cell for aluminum production, the electrolyte comprises aluminum fluoride and sodium fluoride and the metal oxide is alumina. The weight ratio of sodium fluoride to aluminum fluoride is about 0.7 to 1.25, preferably about 1.0 to 1.20. The electrolyte may also contain calcium fluoride, lithium fluoride and/or magnesium fluoride.

While the invention has been described in terms of preferred embodiments, various changes, additions and modifications may be made without departing from the scope of the invention as set forth in the following claims.

CLAIMS

1. A method of producing commercial purity aluminum comprising:

passing current between an inert anode and a cathode through a bath comprising an electrolyte and aluminum oxide; and

recovering aluminum comprising a maximum of 0.20 weight percent Fe, 0.1 weight percent Cu, and 0.034 weight percent Ni.

2. The method of claim 1, wherein the inert anode comprises Fe or a compound thereof.

3. The method of claim 1, wherein the inert anode comprises Cu or a compound thereof.

4. The method of claim 1, wherein the inert anode comprises Ni or a compound thereof.

5. The method of claim 1, wherein the inert anode comprises Fe, Cu and Ni, or compounds thereof.

6. The method of claim 1, wherein the inert anode is made from Fe_2O_3, NiO and ZnO.

7. The method of claim 6, wherein the inert anode further comprises at least one metal selected from Cu, Ag, Pd, Pt, Au, Rh, Ru, Ir and Os.

8. The method of claim 7, wherein the at least one metal is selected from Cu, Ag, Pd and Pt.

9. The method of claim 7, wherein the at least one metal comprises Cu and at least one of Ag and Pd.

10. The method of claim 7, wherein the at least one metal comprises Ag.

11. The method of claim 10, wherein the Ag is provided from Ag_2O.

12. The method of claim 1, wherein the inert anode comprises at least one ceramic phase of the formula $Ni_{1-x-y}Fe_{2-x}M_y O_4$, where M is Zn and/or Co, x is from 0 to 0.5 and y is from O to 0.6.

13. The method of claim 12, wherein M is Zn.

14. The method of claim 13, wherein x is from 0.05 to 0.2 and y is from 0.01 to 0.5.

15. The method of claim 12, wherein M is Co.

16. The method of claim 15, wherein x is from 0.05 to 0.2 and y is from

0.01 to 0.5.

17. The method of claim 1, wherein the inert anode is made from a composition comprising about 40.48 weight percent Fe_2O_3, about 43.32 weight percent NiO, about 0.2 weight percent ZnO, about 15 weight percent Cu, and about 1 weight percent Pd.

18. The method of claim 1, wherein the inert anode is made from a composition comprising about 57 weight percent Fe_2O_3, about 27.8 weight percent NiO, about 0.2 weight percent ZnO, about 15 weight percent Cu, and about 1 weight percent Pd.

19. The method of claim 1, wherein the inert anode is made from a composition comprising about 56.9 weight percent Fe_2O_3, about 27.9 weight percent NiO, about 0.2 weight percent ZnO, about 14 weight percent Cu, about 0.95 weight percent Ag, and about 0.05 weight percent Pd.

20. The method of claim 1, wherein the inert anode is made from a composition comprising about 55.95 weight percent Fe_2O_3, about 27.35 weight percent NiO, about 1.7 weight percent ZnO, about 14 weight percent Cu, about 0.9 weight percent Ag, and about 0.1 weight percent Pd.

21. The method of claim 1, wherein the inert anode is made from a composition comprising about 55.23 weight percent Fe_2O_3, about 27.21 weight percent NiO, about 1.68 weight percent ZnO, about 14.02 weight percent Cu, and about 1.86 weight percent Ag_2O.

22. The method of claim 1, wherein the recovered aluminum comprises a maximum of 0.15 weight percent Fe, 0.034 weight percent Cu, and 0.03 weight percent Ni.

23. The method of claim 1, wherein the recovered aluminum comprises a maximum of 0.13 weight percent Fe, 0.03 weight percent Cu, and 0.03 weight percent Ni.

24. The method of claim 1, wherein the recovered aluminum further comprises a maximum of 0.2 weight percent Si, 0.03 weight percent Zn, and 0.03 weight percent Co.

25. The method of claim 1, wherein the recovered aluminum comprises a maximum of 0.10 weight percent of the total of the Cu, Ni and Co.

FIG. 1

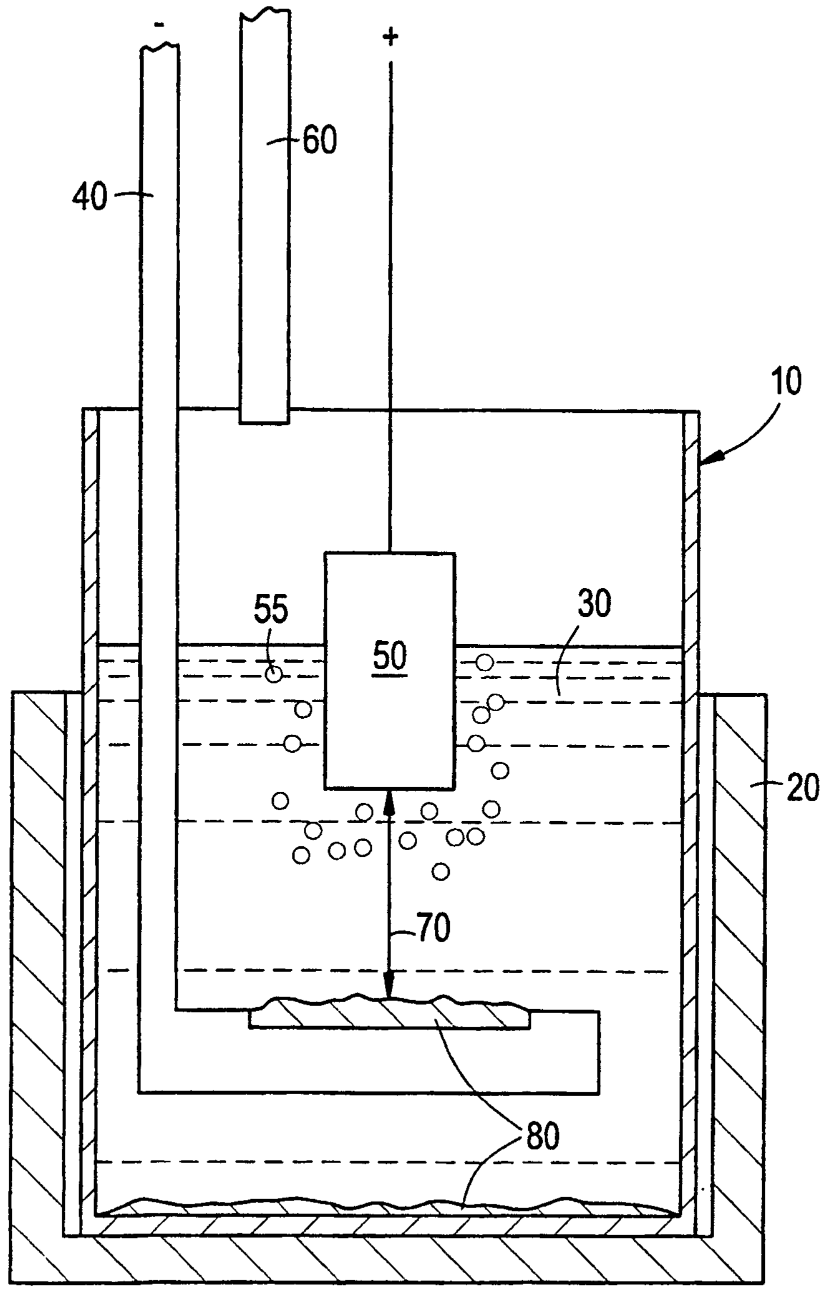
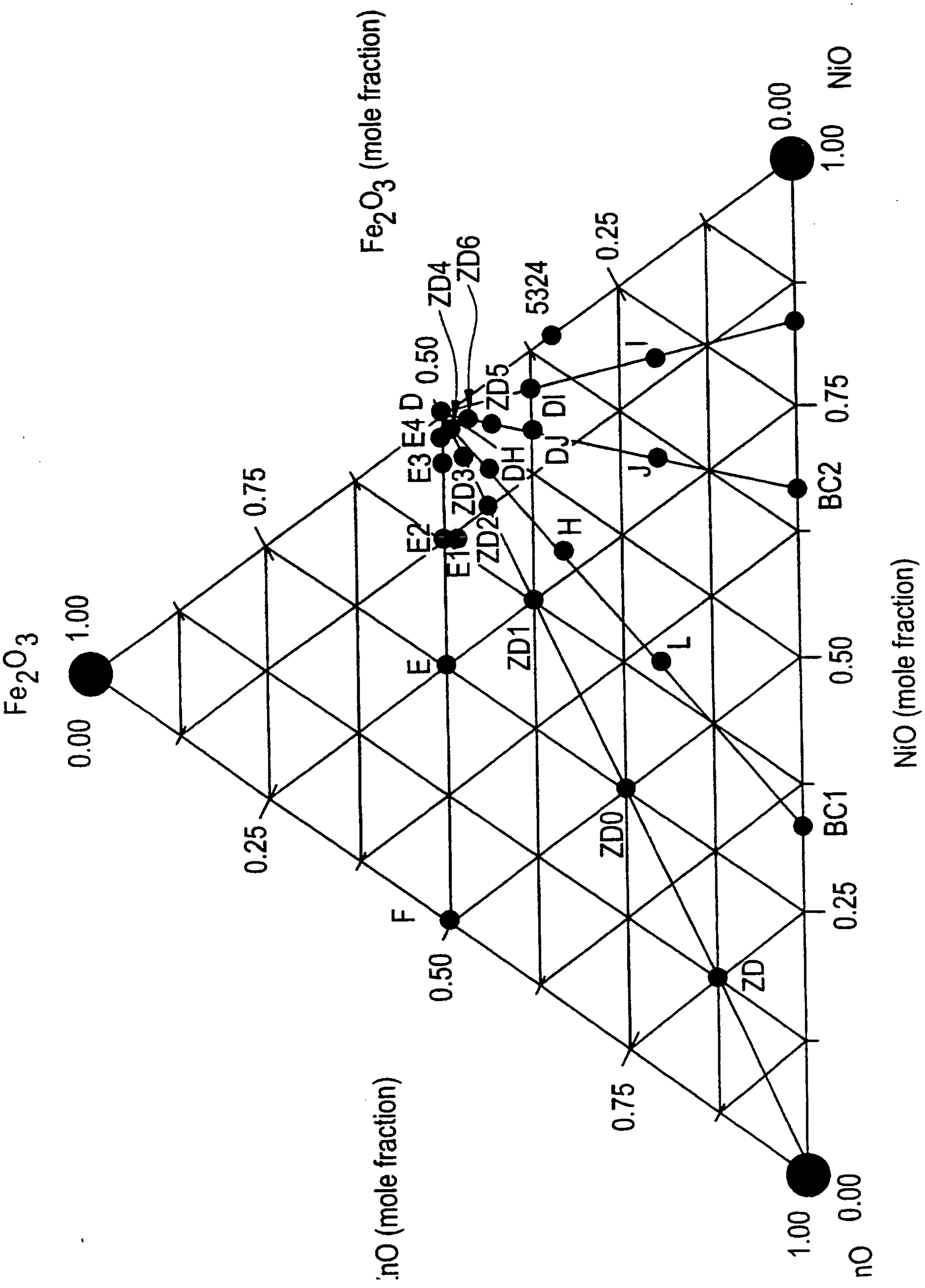


FIG. 2


Fe2O3
Fe2O3 (mole fraction)
NiO (mole fraction)
ZnO (mole fraction)
NiO
ZnO
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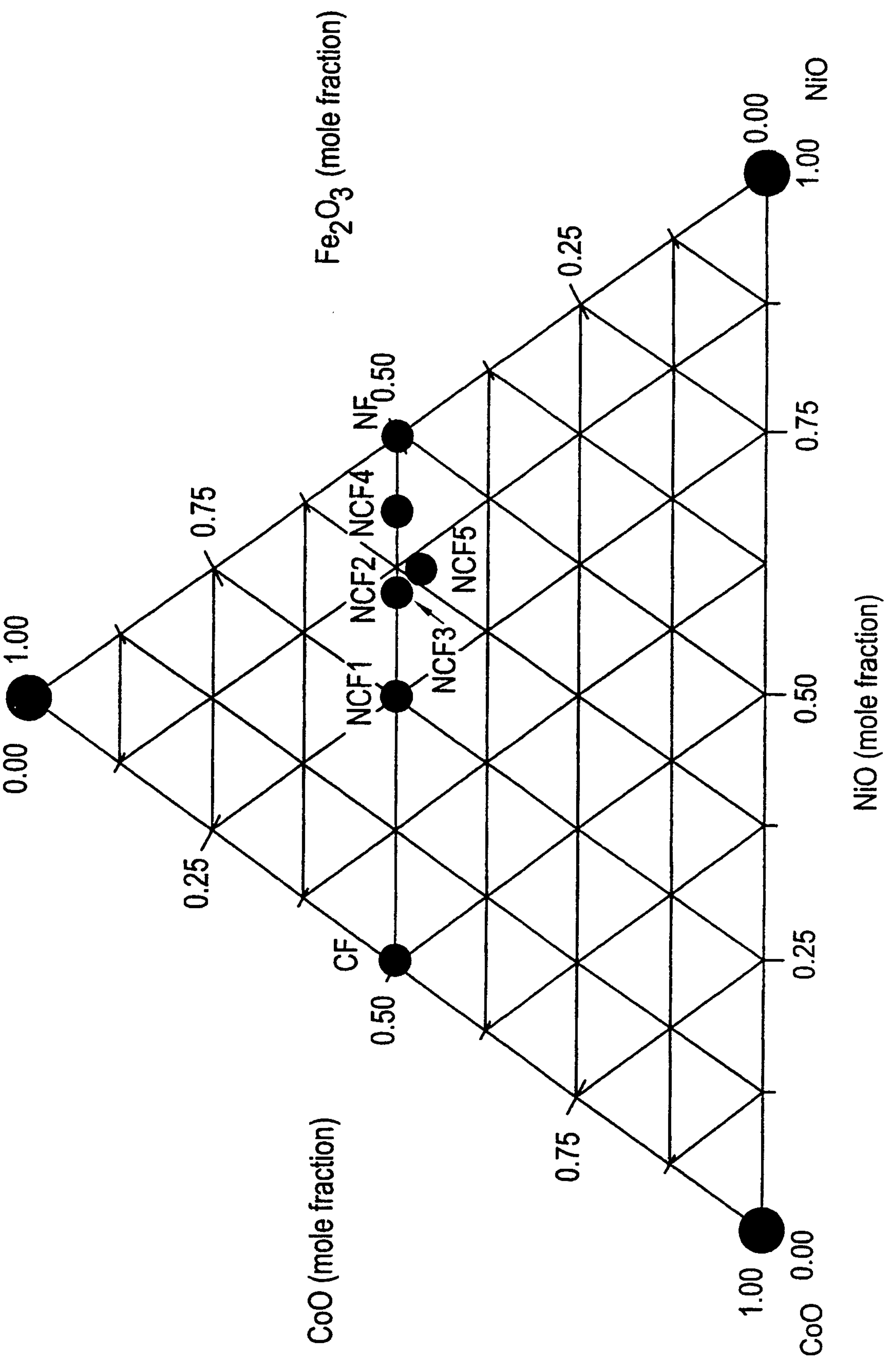
0.25
0.50
0.75
1.00
E
F
E1
E2
E3
E4
D
DI
DJ
DH
H
I
J
L
ZD
ZD0
ZD1
ZD2
ZD3
ZD4
ZD5
ZD6
5324
BC1
BC2

FIG. 3


Fe_2O_3
0.00
1.00
Fe_2O_3 (mole fraction)
NiO
0.00
1.00
NiO (mole fraction)
CoO (mole fraction)
CoO
1.00
0.00
0.25
0.50
0.75
CF
NF
NCF1
NCF2
NCF3
NCF4
NCF5

INTERNATIONAL SEARCH REPORT

Int tional Application No
PCT/US 00/29825

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 C25C3/12 C25C3/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 C25C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, CHEM ABS Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 455 211 A (SIBA P. RAY) 19 June 1984 (1984-06-19) column 9, line 22 - line 34	1,2,4
X	US 4 552 630 A (DOUGLAS J. WHEELER) 12 November 1985 (1985-11-12) column 5, line 34 - line 40 example 15; table 3 column 8 -column 10; claims 1-26	1,2,4,6, 12,13
P,X	WO 00 44952 A (ALCOA INC.) 3 August 2000 (2000-08-03) see whole docu,ment	1-25

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 February 2001	23/02/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Groseiller, P

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 00/29825

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			NO	812636	A	03-08-1981
			NO	155670	B	26-01-1987
			NZ	195755	A	15-03-1983
			RO	83300	A	23-05-1984
			TR	21026	A	20-05-1983
			WO	8101717	A	25-06-1981
			YU	308980	A	30-04-1983
			ZA	8007586	A	25-11-1981
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			US	6126799	A	03-10-2000
			US	6162334	A	19-12-2000
			US	6030518	A	29-02-2000

Sodium Chloride, NaCl, Selected Properties of Aqueous Solutions at 20° C.

Interpolated Data		Calculated Data			Components @ 20°C Calculated from M	
CRC 62nd, Table 71, p. D-232, 20°C						
Wt. % NaCl	*S.G @ 20°C	NaCl, g/L	H_2O, g/L	Molarity, M	Cl-, g/L	Na+, g/L
0.00	1.0000	0.0	1000.0	0.000	0.0	0.0
0.50	1.0036	5.0	996.8	0.086	3.0	2.0
1.00	1.0071	10.1	995.3	0.173	6.1	4.0
1.50	1.0107	15.1	993.8	0.258	9.2	5.9
2.00	1.0143	20.2	992.2	0.346	12.3	7.9
2.50	1.0178	25.4	990.6	0.435	15.4	10.0
3.00	1.0214	30.6	989.0	0.524	18.6	12.0
3.40	1.0243	34.8	987.7	0.595	21.1	13.7
3.45	*1.0247*	*35.4*	*987.6*	*0.604*	21.4	13.9
3.50	**1.0250**	**35.8**	**987.4**	**0.613**	**21.7**	**14.1**
3.55	*1.0254*	*36.4*	*987.3*	*0.622*	22.1	14.3
3.60	1.0257	36.9	987.1	0.631	22.4	14.5
4.00	1.0286	41.1	985.7	0.703	24.9	16.2
4.50	1.0322	46.4	984.0	0.794	28.1	18.3
5.00	1.0358	51.7	982.3	0.885	31.4	20.3
5.50	*1.0395*	*57.1*	*980.6*	*0.977*	34.6	22.5
6.00	1.0431	62.5	978.8	1.069	37.9	24.6

FW Na	22.990
FW Cl	35.453
FW NaCl	58.443
X_{Na} in NaCl	**0.39337**
X_{Cl} in NaCl	**0.60663**
X_{total}	**1.00000**

Density of Water
(CRC 62nd Ed. p. F-11)

T/°C	T/°F	ρ, g/l
15	59.0	0.99913
18	64.4	0.99862
20	**68.0**	**0.99823**
23	*73.4*	*0.99753*
25	77.0	0.99707

For pure water only:
S.G. = ρ at all T

***Expected hydrometer readings @ 20°C.**
Definition: Specific gravity of solution @ 20°C = (density of solution @ 20°C)/ (density of pure H_2O @ 3.98°C), dimensionless.
Our hydrometers are readable only to 3 decimal places.
Thus, they may not clearly distinguish solutions whose concentrations differ by much less than 0.1 wt.% NaCl.
Tank records show typical equilibrium tank temperatures of 72°F - 74°F. Winter inlet water temperatures as low as ~50°F.